MULTI-SCALE HYBRID TOPOLOGY OPTIMISATION: FOR ADDITIVE MANUFACTURING SHELL ENVELOPES USING ADVANCED ALGORITHMS

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The synthesis of shell shapes for robotic Additive Manufacturing (AM) with earth-based composites is crucial due to rapid hardware advancements, increased AM accessibility, and the drive for sustainable construction. Shell structures, known for their material efficiency, design flexibility, and load-bearing capabilities, often face deformation and failure during construction, especially when using earthen and cement-based materials. The traditional masonry shells capitalize on compression strengths, AM introduces challenges such as increased tensile stresses, bending moments, and the necessity for supports in cantilevered sections. Addressing these issues is key to advancing sustainable shell envelope construction through robotic AM. Advances in computational framework methods are introduced, enabling the design and mass customization of shell envelopes to explore various design scenarios suitable for construction AM, focusing on self-supporting surfaces that utilize ribbed systems to enhance structural efficiency. The development of *HybridOpt*, a C# based Grasshopper plugin, is presented as a tool to establish a seamless connection between Grasshopper and SAP2000v24 via its Open Application Programming Interface (OAPI) in C# for a comprehensive analysis of shell maximum stresses and strain. The computational framework integrates the Bidirectional Evolutionary Structural Optimization (BESO) method to enable mass customization of ribs while leveraging finite element analysis (FEA) software. Additionally, Karamba3D, a Grasshopper plugin, performs principal stress analysis within the shell envelope, enhancing structural performance evaluation and optimization of the shell mass and strain energy. Furthermore, the acquired technique explores the effects of topology optimization strategy on the structural performance of AM shell envelopes, offering a comprehensive computational framework for the future construction of AM applications.

INTRODUCTION

Topology optimization

Topology optimization has emerged as a pivotal tool in engineering design, offering a systematic approach to achieving optimized structural layouts within specified design domains, guided by particular objectives and constraints. This methodology is especially valuable in industrial applications due to its minimal requirement for prior design knowledge, making it accessible and efficient for a wide range of applications. The foundational work by Bendsøe and Kikuchi (1988) introduced homogenization-based topology optimization, which has since become the basis of the field. Despite its potential, the single-scale reconstruction of homogenized results presents challenges, particularly in approximating the conformality and periodicity of multi-scale structures on a finite length scale [1].

Topology optimization is a computational technique that optimizes material distribution within a design domain to enhance structural performance under given constraints. It systematically removes low-stressed material while ensuring minimal variations in the stiffness matrix throughout subsequent optimization steps[1].

The goal is to find the structural layout that best transfers specific loading conditions to supports, thereby generating an acceptable initial layout of the structural system, which can then be refined through shape optimization procedures.

In the context of structural engineering, topology optimization can be employed to assist designers in defining a structural system that best satisfies operating conditions.

The integration of topology optimization into commercial software, such as SAP2000V24, is facilitated through the use of an open application programming interface (API)[1,2].

Shell Structures for AM

Shell structure optimization in structural engineering demonstrates superior efficiency, providing an optimal balance between mass minimization and mechanical strength. This characteristic renders shell structures particularly advantageous for A dditive M anufacturing (AM) applications.

The utilization of shell geometries, as opposed to solid counterparts, yields significant benefits in terms of material economy and fabrication speed, thereby reducing overall production costs.

In cases where shell morphologies are dictated by factors beyond external load distributions, structural enhancement is often necessary. This is typically achieved through localized reinforcement strategies, such as:

- Selective thickness augmentation in critical regions
- Integration of ribbed support structures

These methods aim to improve the load-bearing capacity and overall structural integrity of the shell without compromising its inherent lightweight properties. The optimization of such reinforcement strategies remains an active area of research in computational design for AM, focusing on the balance between material usage and mechanical performance [3].

Ribbed-shell structures

These structures are designed to enhance the mechanical performance of shell structures by adding ribs along principal stress lines.

The ribs are closely attached to the shell, which helps in utilizing the bending characteristics and avoiding stress concentration, thus providing better stability compared to other supporting structures like pillars or frames.

The ribbed-shell structures are advantageous because they do not occupy much internal space and can have variable cross-sectional shapes to meet different performance goals [3].

Shell stresses

Principal Stresses: are the components of a stress tensor when the basis is changed such that the shear stress components become zero. The stress tensor has three real eigenvalues and three mutually orthogonal eigenvectors, which are used to determine the principal stress directions. These directions indicate trajectories of internal forces and naturally encode the optimal topology for any structure under given boundary conditions.

Von Mises stress is widely used to predict the yielding of materials under any loading condition. It is a scalar derived from the Cauchy stress tensor and is used in the system to ensure that the material does not exceed its yield strength. The von Mises stress is calculated using the formula that involves the orthogonal normal stresses and orthogonal shear stresses.

Stress computation and optimization: the process of setting up the static equilibrium equation of rib-reinforced shells to calculate nodal displacements using the Finite Element Method FEM. This involves re-meshing the surface so that all ribs lie on the edges of the resultant triangular mesh, and modeling each rib as beam elements. The contribution of the ribs to the shell is obtained by superimposing the element stiffness matrix of the ribs onto the shell's stiffness matrix. The optimization aims to minimize material usage while achieving the required structural stiffness [3].

Problem formulation

Achieving optimal mass distribution and structural stability in shell envelopes fabricated through robotic Additive Manufacturing (AM) with earth-based composites presents a critical challenge.

Due to the material's low tensile strength and vulnerability to deformation, shell structures must be designed to minimize bending moments and tensile stresses while ensuring load-bearing capacity.

Traditional approaches rely on experience-based heuristics to define the thickness and reinforcement of shell structures, often leading to inefficient material use or inadequate structural performance.

To address these limitations, the Bidirectional Evolutionary Structural Optimization (BESO) method is employed to systematically optimize the mass distribution of the shell envelope, ensuring that material is concentrated in regions that contribute most to load-bearing efficiency while reducing unnecessary mass.

The BESO method, integrated within the AMEBA topology optimization plugin, is used to define the structural optimization and computational framework.

Within this framework, load types (such as self-weight, live loads, and wind pressure), principal stresses simulations, are systematically applied to the shell, while

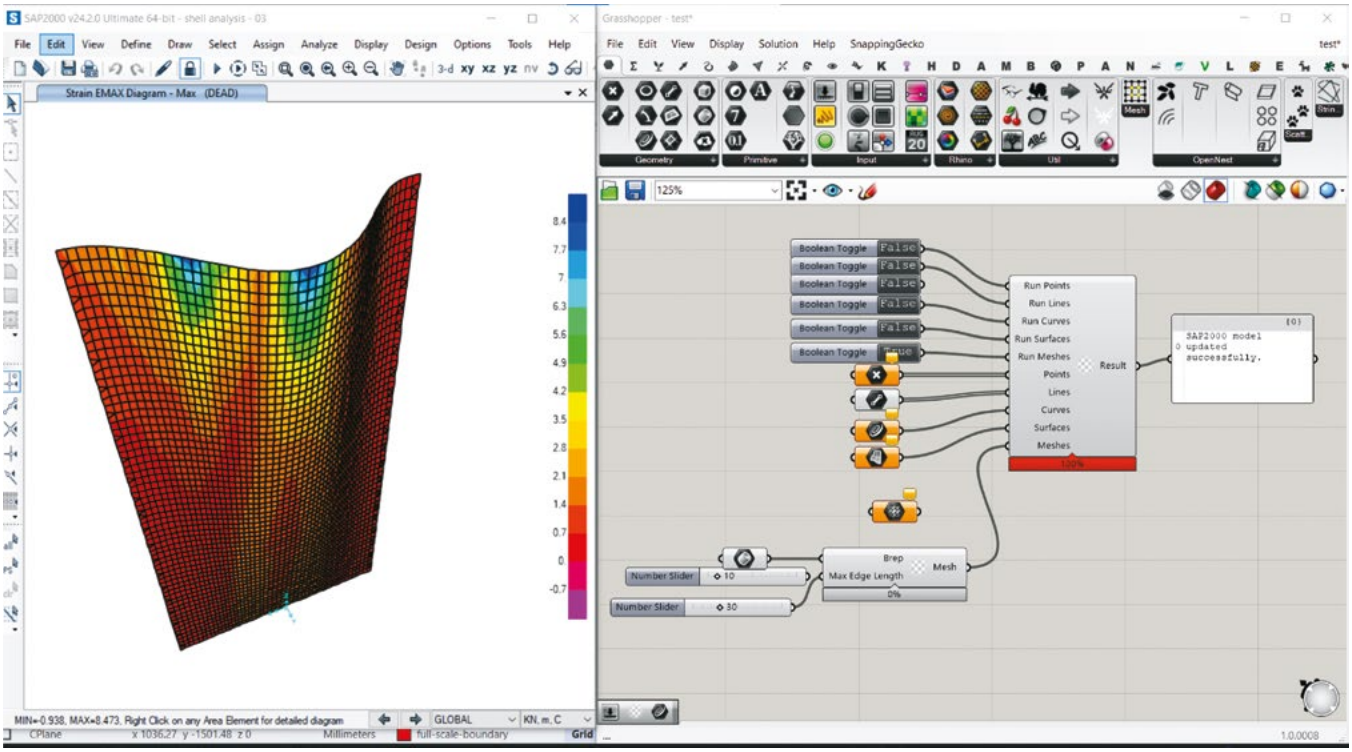

Figure 1: Developed the *HybridOpt* Grasshopper plugin to establish a seamless link between Grasshopper and SAP2000v24, while also implementing an advanced computational framework for stress analysis.

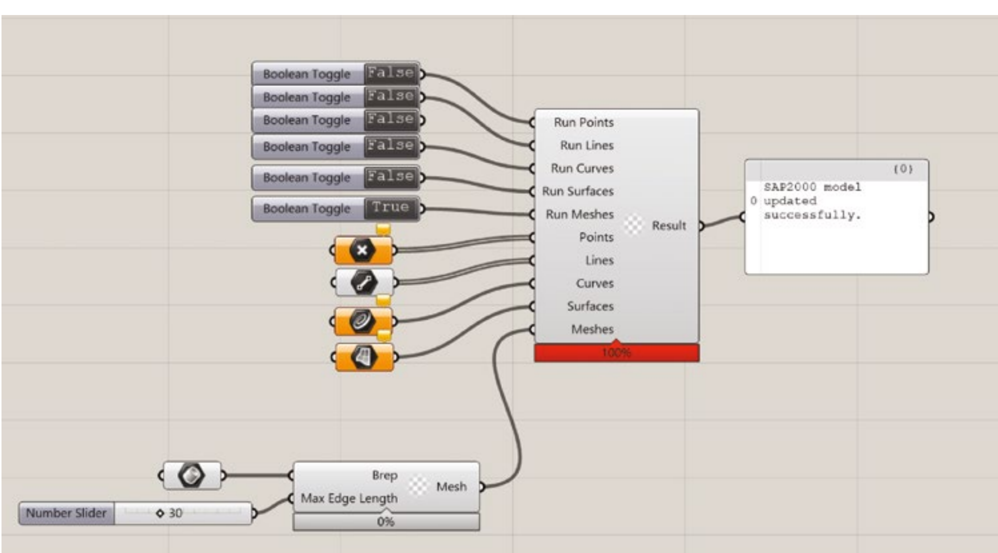

Figure 2: Developed a C# component for generating a mesh subdivision and Livelink suite in (SAP2000v24).

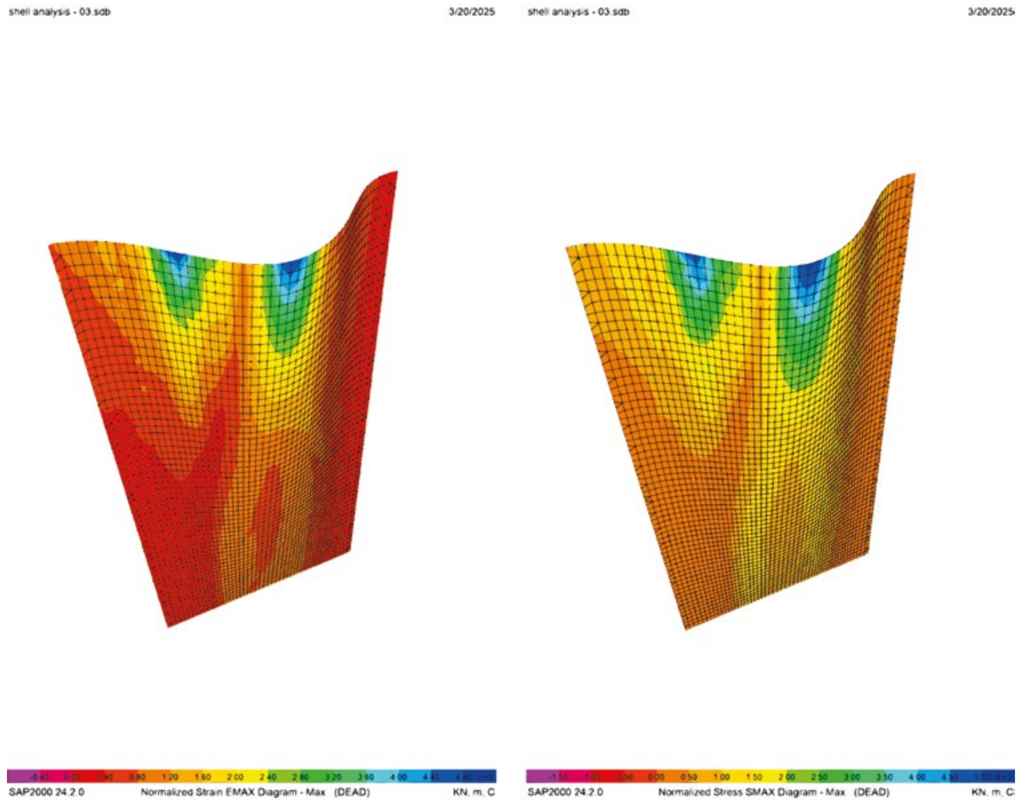

Figure 3: The normal stress and strain principal direction in 3D, indicating the tensile and compressive stress along shell envelop, SAP2000v24.

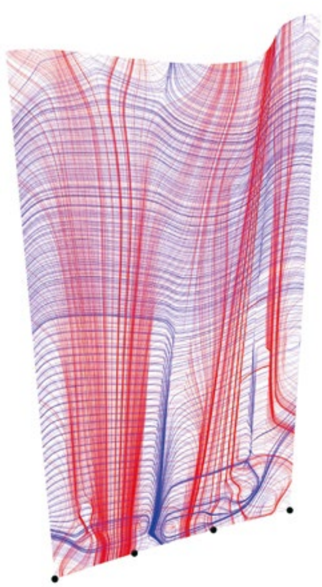

Figure 4: Principal moment lines in a vertical shell element under load, showing how bending forces flow to the supports at the base (red indicating the major principal moments, blue the minor).

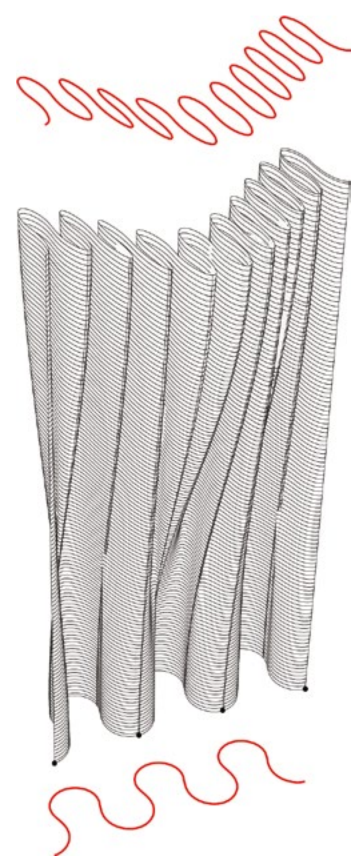

Figure 5: The shell geometry's ribs are aligned with the maximum stress directions to optimally distribute mass and enhance structural efficiency.

anchor points are strategically positioned at critical support or ribs locations to enhance stability in the construction AM process.

The design domain is established to encompass the entire shell geometry, allowing for the gradual evolution of an optimized form that maximizes structural performance.

Additionally, boundary conditions including fixed ribs supports are carefully defined to reflect realistic constraints in construction AM scenarios.

The material properties of earth-based composites, including compressive and tensile strength, Young's modulus, and density, are incorporated into the optimization process to ensure accurate structural stress and strain simulation analysis with developed Livelink into data base software SAP2000V24 for an accurate result.

Livelink between Grasshopper and (SAP2000v24)

Developing a C# Grasshopper component that creates a live link between the geometries generated in Grasshopper and Rhinoceros 8, while the stress analysis performed in (SAP2000v24). This integration allows precise stress analysis of the shell structures, helping to identify potential failure points and optimize the design early in the process.

The *Hybridopt* C# script is a Grasshopper developed plugin component that establishes a live link with SAP2000v24 for structural analysis. It imports key libraries for handling geometry (Rhino.Geometry), Grasshopper integration (Grasshopper.Kernel), and SAP2000 API interaction (SAP2000v1). Encapsulated within the Hybridopt namespace, it extends GH_Component, inheriting Grasshopper functionalities. The component initializes two private variables, cOAPI mySapObject (SAP2000 API connection) and cSapModel mySapModel (structural model), enabling real-time export of points, lines, curves, surfaces, and meshes for SAP2000v24 simulations.

```
using System.Collections.Generic;
using Grasshopper;
using Grasshopper.Kernel;
using Rhino.Geometry;
using SAP2000v1;
namespace Hybridopt
{
public class HybridoptComponentV24 : GH_Component
{
private cOAPI mySapObject;
using System;
private cSapModel mySapModel;
public HybridoptComponentV24()
: base("HybridoptComponentV24", "Hybrid-opt",
"Live link between Grasshopper and SAP2000",
"Category", "Subcategory")
{
}
protected override void RegisterInputParams(GH_Component.GH_InputParamManager pManager)
{
pManager.AddBooleanParameter("Run Points", "RP", "Run the SAP2000 script for points", GH_ParamAccess.item);
pManager.AddBooleanParameter("Run Lines", "RL", "Run the SAP2000 script for lines", GH_ParamAccess.item);
pManager.AddBooleanParameter("Run Curves", "RC", "Run the SAP2000 script for curves", GH_ParamAccess.item);
pManager.AddBooleanParameter("Run Surfaces", "RS", "Run the SAP2000 script for surfaces", GH_ParamAccess.item);
pManager.AddBooleanParameter("Run Meshes", "RM", "Run the SAP2000 script for meshes", GH_ParamAccess.item);
pManager.AddPointParameter("Points", "P", "List of points to export", GH_ParamAccess.list);
pManager.AddLineParameter("Lines", "L", "List of lines to export", GH_ParamAccess.list);
pManager.AddCurveParameter("Curves", "C", "List of curves to export", GH_ParamAccess.list);
pManager.AddSurfaceParameter("Surfaces", "S", "List of surfaces to export", GH_ParamAccess.list);
pManager.AddMeshParameter("Meshes", "M", "List of meshes to export", GH_ParamAccess.list);
}
protected override void RegisterOutputParams(GH_Component.GH_OutputParamManager pManager)
{
pManager.AddTextParameter("Result", "R", "Result of the SAP2000 script", GH_ParamAccess.item);
```

This C# script converts a Brep into a Mesh while controlling the maximum edge length of mesh faces. The Solve Instance method retrieves a Brep input and an optional edge length parameter (maxEdgeLength), defaulting to 1.0. If valid data is provided, it calls BrepToMesh(maxEdgeLength), converting the Brep into a mesh using custom BrepExtensions.

The Brep extensions class defines BrepToMeshes, which generates a mesh array using Meshing Parameters, and Join Meshes, which merges multiple meshes into a single entity. The resulting optimized mesh is then output in Grasshopper for further processing.

```
protected override void SolveInstance(IGH_DataAccess DA)
{
```

```
Brep brep = null;
double maxEdgeLength = 1.0;
if (!DA.GetData(0, ref brep)) return;
if (!DA.GetData(1, ref maxEdgeLength)) return;
Mesh mesh = brep.BrepToMesh(maxEdgeLength);
DA.SetData(0, mesh);
}
public override Guid ComponentGuid => new Guid("1a6e45b7-6e2b-4d8c-82e9-8a3a7a6fce2d");
protected override System.Drawing.Bitmap Icon => null; // Add an icon if available
}
public static class BrepExtensions
{
public static List<Mesh> BrepToMeshes(this Brep brep, double maxEdge)
{
Mesh[] mesh;
MeshingParameters mp = new MeshingParameters
{
MaximumEdgeLength = maxEdge
};
mesh = Mesh.CreateFromBrep(brep, mp);
return mesh.ToList();
}
public static Mesh JoinMeshes(this List<Mesh> meshes)
{
var rtnmesh = new Mesh();
foreach (Mesh mesh in meshes)
{
rtnmesh.Append(mesh);
}
return rtnmesh;
}
public static Mesh BrepToMesh(this Brep brep, double maxEdge)
{
return JoinMeshes(BrepToMeshes(brep, maxEdge));
}
```

Structure Optimization Framework

Beyond mass optimization, rib topology takes a crucial role in reducing buckling effects and minimizing strain energy in the shell envelope.

By leveraging the AMEBA plugin for topology optimization, rib placement is guided by principal stress trajectories, ensuring reinforcement is provided where the shell experiences maximum compressive and tensile forces.

This strategic rib layout enhances global stiffness, reduces deformation under load, and improves the structural integrity of thin shell sections, which are highly susceptible to buckling. Furthermore, by optimizing rib topology, the framework effectively reduces strain energy concentration, leading to a more uniform stress distribution across the shell.

By integrating BESO-based mass optimization and rib topology refinement, this research provides a computational framework that enhances the efficiency and feasibility of AM-fabricated shell structures.

The proposed method not only improves structural performance but also aligns with sustainable construction principles by minimizing material waste while maximizing load-bearing efficiency. Topology Optimization of Shell envelopes: developing an algorithm using (BESO) computational framework implemented in AMEBA plugin within Grasshopper, which optimizes the material distribution in the shell envelope.

This tool is crucial for adjusting the rib mass and shell mass to improve the overall structural performance of the AM shell.

The Bidirectional Evolutionary Structural Optimization (BESO) framework provides a powerful method for optimizing material distribution within a structure by iteratively removing inefficient material while reinforcing critical load-bearing regions.

Unlike gradient-based optimization approaches, which allow for gradual material transitions, BESO employs a binary material distribution strategy, systematically converting regions into either solid or void.

This discrete adjustment ensures that only structurally essential material remains, leading to an efficient mass distribution that enhances performance while reducing material waste.

The exploration of these previous aspects serves the main purposes: minimizing strain energy and maximizing structural stiffness.

To accomplish these objectives, we present a computational framework for building an advanced Grasshopper algorithm using KARAMBA 3D and SAP2000V24 that simulates and analyzes computationally shell stress distribution lines. Our strategy focuses on strategically placing rib mass along primary stress paths, enhancing the stiffness of the shell, and optimizing its structural integrity. This tailored approach is geared toward maximizing mechanical effectiveness, particularly suited for the intricacies of construction 3d printing [2,4].

BACKGROUND

The rib-reinforced shell structures, a computational framework has been developed to enhance the structural strength and stiffness of shells by integrating ribs along principal stress lines. This approach ensures that the ribs follow paths of material continuity, which are indicative of internal force trajectories. The framework involves several stages, including the generation of a dense rib network, simplification of the network by removing non-contributory ribs, and optimization of rib flow and cross-section. The ribs are designed to swing on the surface, allowing for adjustments that improve structural performance.

The principal stress lines, which guide the rib placement, are calculated using Finite Element Analysis (FEA) on the shell structure. This analysis provides a principal stress field that is used to generate a quad-mesh, aligning the mesh edges with the stress directions5. The rib network is then extracted from this mesh, ensuring that the ribs are optimally placed to reinforce the shell. The optimization process also includes the use of hyperelliptic T-sections for the rib cross-sections, which help in reducing stress concentration and improving mechanical performance. This method has been validated through experimental results, demonstrating that rib-reinforced shell structures achieve significantly higher strength and stiffness compared to pure shells of the same material volume [3].

In recent years, construction AM, particularly with concrete and earth, has seen significant advancements, necessitating the development of new shape-design methods. Bhooshan introduced the concept of Function Representation to address the challenges of spatial coherence in print paths, which is crucial for ensuring that each layer of material has sufficient overlap with the preceding one. This approach contrasts with the traditional 'slicing' paradigm, which often lacks spatial coherence and requires significant domain expertise.AM through a combination of shape interpolation (Morph) and affine interpolation. This method reduces the expertise needed to create complex, nearly-print-ready shapes and provides visual feedback regarding the constraints of concrete and earth printing. The Morph & Slerp framework is particularly innovative as it adapts ideas from Optimal Mass Transport, a concept historically rooted in the Earthmovers problem, to ensure spatial coherence between print layers. Furthermore, the analogy of concrete or earth printing to masonry design, particularly pitched-brick vaulting, is a significant precedent for this work. The historic masonry structures, showing that they are composed of simpler geometric primitives laid along self-supporting arched courses, similar to AM along print paths. This historical context provides a foundation for understanding the potential of the proposed shape-design methods in modern 3D printing applications [4].

METHOD

This research paper employs a computational framework that combines topology optimization, finite element analysis (FEA), and principal stress evaluation to design and optimize additively manufactured AM shell envelopes.

The framework integrates the Bidirectional Evolutionary Structural Optimization (BESO) method for mass customization of ribs, ensuring that structural material is allocated efficiently in regions of high stress. In parallel, a standard FEA solver is utilized to compute principal stress distributions, displacements, and strain energy, forming the foundation for iterative design updates as shown in Figure 6 , and Figure 7.

This dual approach (topology optimization + FEA) aims to maximize structural performance while minimizing material usage, thereby reducing weight ,time and cost for large-scale AM applications.

Geometry Definition and Ribs Setup

The process begins with defining the shell envelope geometry in a parametric modeling environment. The geometry is discretized into a finite element mesh suitable for both the BESO algorithm and FEA. Key input parameters such as material properties, boundary conditions, loading scenarios, ribs topology and target volume reduction are specified to guide the optimization.

Once the mesh and constraints are established, the initial shell model is analyzed under load to determine baseline stress and displacement values.

BESO-Driven Topology Optimization

The BESO method iteratively refines the shell structure by adding or removing material in regions of low or high stress, respectively.

The algorithm identifies areas underutilized in carrying load and systematically eliminates them, while simultaneously reinforcing high-stress regions or mentioning the potential ribs regions.

This bidirectional approach preserves a continuous load path throughout the optimization process, maintaining structural integrity. At each iteration, the updated geometry is reanalyzed with FEA to capture the evolving stress distribution. Convergence is achieved when predefined criteria such as minimal strain energy, maximum stiffness, or targeted mass reduction are met as shown in the results and Figure 6 , Figure 7 , Figure 8 , and Figure 9.

Principal Stress Analysis with Karamba3D

In parallel to the BESO optimization, Karamba3D (a Grasshopper plugin for structural analysis) is employed to evaluate principal stresses within the shell as shown in Figure 4. By visualizing major and minor principal stress lines, to identify critical load paths and potential stress concentrations. These insights guide the strategic placement and orientation of ribs, ensuring they align with principal

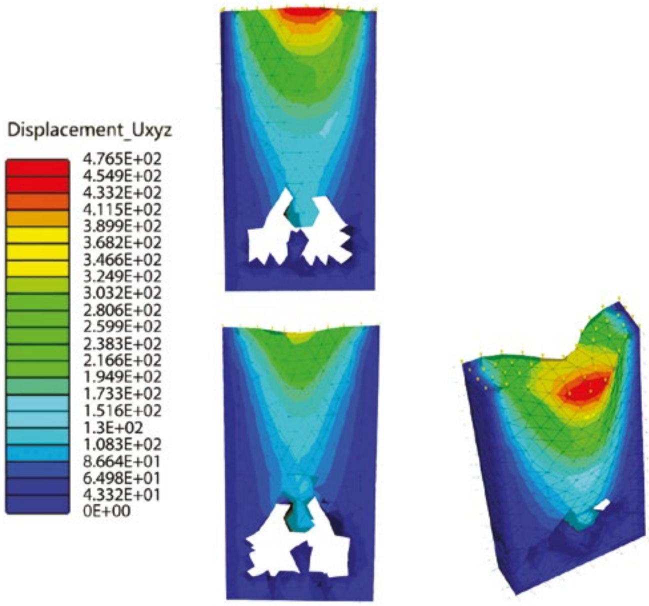

Figure 6: Displacement contours (Uxyz) for the shell envelop wall, illustrating how the structure deforms under applied load.

Figure 7: The final iteration achieves a volume fraction of approximately 0.95 while stabilizing the total strain energy near 3.74×10^6.

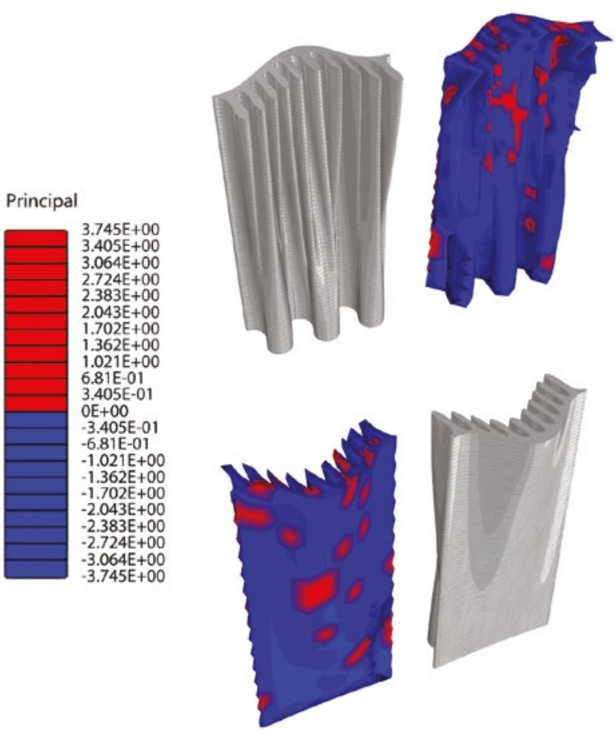

Figure 8: Principal stress distribution in the ribbed shell configuration, where positive (tensile) stresses appear in red and negative (compressive) stresses in blue. The ribbed geometry effectively redistributes loads, reducing high-stress concentrations and enhancing overall structural performance.

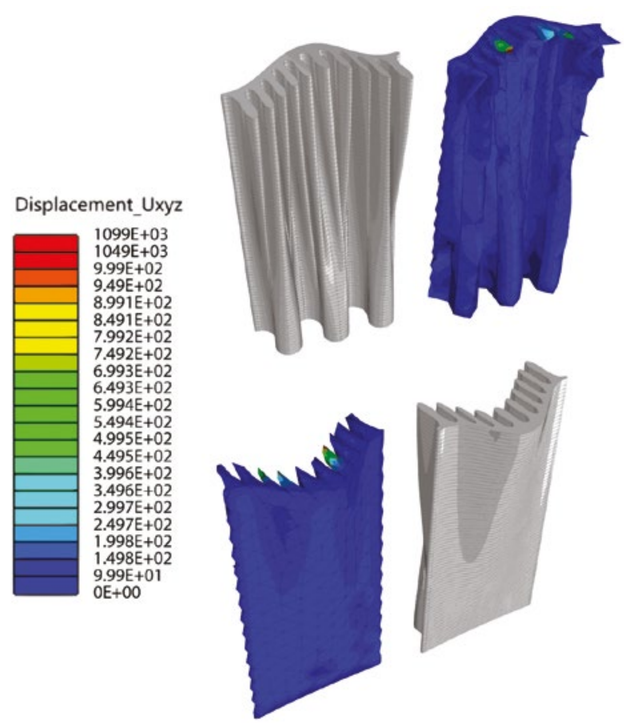

Figure 9: Displacement contours (Uxyz) for the ribbed shell configuration, illustrating deformation under applied loading. The color scale transitions from blue (minimal displacement) to red (maximum displacement, approximately 1.10×10^3, indicating that the ribbed geometry effectively minimizes overall deformation by improving load distribution and structural stiffness.

Figure 10: The initial spike in volume fraction quickly stabilizes, converging to approximately 0.975 by iteration 11, with total strain energy settling near 2.13×10^4.

Figure 11: Scaled prototype 1:10 3D printed using a laboratory robot at IAAC Institute for Advanced Architecture of Catalonia and nozzle 25mm, demonstrating controlled cavity design to reduce buckling and displacement.

Figure 12: Extrusion test of a 1:10 scale shell geometry using a 15 mm nozzle, based on a rib-reinforced computational design method.

stress trajectories. The combined use of Karamba3D and a standard FEA solver provides a robust validation mechanism: Karamba3D highlights qualitative stress patterns, while the FEA offers detailed quantitative results for accurate performance assessment.

Iterative Refinement and Validation

After each optimization cycle, the refined geometry undergoes FEA to confirm that strength, stiffness, and serviceability requirements are satisfied. The resulting stress and displacement fields inform further adjustments to the shell thickness, rib layout, or material distribution. This loop continues until the design meets the desired performance thresholds with minimal material usage. Finally, the optimized geometry is post-processed for manufacturability, ensuring that rib thickness, curvature, and overall shell dimensions are feasible for large-scale additive manufacturing.

RESULTS

In the final numerical results, The case 1 as shown in Figure 6 , and Figure 7, featuring converged to a volume fraction of approximately 0.95, indicating a 5% mass reduction while maintaining a relatively total strain energy of about 3.74×10^6. Correspondingly, the maximum displacement for this configuration was measured at around 4.76×10^2 showing higher potential of displacement accordingly high stain energy.

In contrast, as shown in Figure 9, and Figure 10. characterized by low principal stresses as shown in Figure 8, concluded with a volume fraction near 0.97 and exhibited minimum total strain energy of 2.13×10^4, along with a less maximum displacement of approximately 1.10×10^3. These results confirm that introducing ribbed shell as shown in Figure 9 reduces both strain energy and displacement under the same boundary conditions, thereby enabling greater mass savings without compromising structural performance. Suggesting effective distribution of load and higher overall stiffness.

REMARK CONCLUSION

A computational methodology for integrating topology optimization into the design processes of AM shell envelopes was developed by leveraging a C# based interface between SAP2000V24 and Grasshopper to simulate stresses based on standard data base, the approach interactive live simulation for model construction, structural analysis, and optimization, allowing for precise material distribution in shell designs, numerical evaluations underscoring the effectiveness of ribbed reinforcement in enhancing overall structural performance for construction 3d printing processes with earth-based materials. The use of SAP2000's Open Application Programming Interface (OAPI) and the *HybridOpt* Grasshopper plugin further streamlines these processes, enabling a practical and interoperable framework for both research and engineering applications. Future studies will expand on this work by refining ribbed reinforcement systems, thereby advancing the performance, feasibility, and scalability of 3D-printed architectural structures.

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